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RESEARCH MEMORANDUM

CHEMICAL IGNITERS FOR STARTING JET FUEL - NITRIC ACID ROCKETS

By Gerald Morrell and Dezso J. Ladanyi

Lewis Flight Propulsion Laboratory
Cleveland, Ohio

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RESEARCH MEMORANDUM

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CHEMICAL IGNITERS FOR STARTING JET FUEL - NITRIC ACID ROCKETS

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SUMMARY

Starting experiments were conducted in a 200-pound-thrust jet fuel - nitric acid rocket with an axial-flow igniter employing the hypergolic (self-igniting) alkyl thiophosphite - nitric acid system. Satisfactory starts were obtained with a ratio of igniter to main-stage thrust of 0.1 at temperatures as low as -80° F. A ratio of igniter to main-stage thrust of 0.05 was marginal at -80° F, but produced satisfactory starts at -50° F.

No combustion instability was observed in the igniter, but many of the main-stage runs exhibited low-frequency oscillations. The onset of these oscillations appeared to coincide with the igniter shutdown, indicating that continuous piloting may be a solution to some of the combustion-instability problems of the jet fuel - nitric acid system.

INTRODUCTION

Since a number of fuels are now known that ignite spontaneously and rapidly with nitric acid over a wide temperature range (ref. 1), chemical starting of the jet fuel - nitric acid rocket-propellant system has become increasingly attractive. As compared with the usual electric ignition system, the chemical system eliminates the need for a warmup period and a multistage igniter. As to weight there is little to choose between the two systems; the additional tank space for the chemical system is offset by the electrical gear for the nonchemical system. Some advantage accrues to the chemical system because the weight of added tank space is partially compensated for by the additional impulse derived from the starting fuel.

Previous research (refs. 2 and 3) has shown that satisfactory starts can be obtained by introducing a self-igniting (hypergolic) fuel in the flow line ahead of the jet fuel. By these means smooth starts were obtained at temperatures near the specification freezing point of jet fuel.

Aside from its simplicity, this technique provides a safety factor when the system is designed to shut down with the hypergolic fuel, so that partially reacted fuel cannot accumulate in the combustor.

In large rocket engines, however, there could be serious disadvantages in this method of starting. Because of the large dimensions of the flow system, larger quantities of igniter fuel would be consumed than would be necessary for ignition. As shown in references 4 and 5, the optimum mixture ratio for ignition is nearly always quite different from that for steady-state operation. Thus, elaborate flow programming would be required to produce the proper mixture ratios through the starting transient. With suppression head starts and the usual fixed-orifice-area injector, poor mixing would result during the ignition period with possibly serious effects on ignition lag (ref. 1).

It appears, then, that for large rockets a separate igniter operating independently of the main-flow system would be desirable, especially where repeated starts are required. The study described in this report evaluated a separate, axial-flow, hypergolic igniter system for jet fuel - nitric acid propellants. The experiments were conducted in a nominal 200-pound-thrust rocket with nominal 10- and 20-pound-thrust igniters. Objectives of the study were to learn what problems, if any, were inherent in this method of starting, especially at low temperatures, and to determine the stabilizing effect of the piloting igniter flames on the transition and subsequent steady-state combustion.

APPARATUS AND PROCEDURE

The apparatus was similar to that used in the study of reference 3, except that no provisions were made for altitude simulation and separate propellant systems were provided for the igniter and main-stage rockets.

Propellant System

The flow system is shown schematically in figure 1, and a photograph of the assembly is shown in figure 2. The toroidal cross section of the main propellant tanks reduced cooling time and minimized propellant temperature variations. The refrigeration system was the same as that shown in figure 4 of reference 2, except that alcohol replaced the methylene chloride refrigerant. For both stages, pneumatically operated Lark missile propellant valves were used. The valve opening rate was varied by adjusting the piloting gas pressure and flow rate.

Engine and Injectors

A cross-sectional view of a rocket engine assembly with the 20-pound-thrust igniter is shown in figure 3. A 10-pound-thrust igniter was also used. The latter had a length of 4.5 inches and a throat diameter of 0.18 inch. A third igniter, designed for 4 pounds thrust, was also fabricated, but its operation was so unreliable (because of the very small injection orifices) that it was not included in the test program. The igniter injectors were fabricated from AISI 347 stainless steel and the igniters from copper bar stock.

The spun-aluminum or copper main-stage cylinders were equipped with a cooling shroud at the nozzle throat. This permitted runs of 3 to 4 seconds at steady state without serious erosion or dimensional changes.

The three main-stage injectors, constructed of AISI 347 stainless steel are shown in figure 4. Injector A, similar to that used in reference 3, produced an inward resultant momentum at design flow. Injector B produced an axial resultant, and injector C was similar to B, except that about 10 percent of the main-stage acid flow was directed into the igniter jet to increase the concentration of oxygen and NO_2 in the combustor.

Instrumentation

Propellant flows were measured by orifices with strain-gage differential pressure transducers, and combustion pressures with strain-gage pressure transducers. Output was delivered to a multichannel recording oscillograph. Estimated errors of these measurements were ±3 percent for flow and ±2 percent for pressure. Under severe resonance conditions the errors were much greater. Valve position was measured by a linear potentiometer.

Propellants

Mixed alkyl thiophosphites and trimethyl trithiophosphite were used interchangeably as igniter fuels. No significant differences in ignition or combustion behavior were observed. Two batches of jet fuel (MIL-F-5624, grade JP-4) taken from laboratory stocks were used. Again, no significant differences in behavior of the batches were observed.

The red fuming nitric acid contained about 20 percent nitrogen dioxide and about 4 percent water.

Operation Procedure

The starting procedure was made fully automatic by means of pressure switches and relays. When the igniter combustion pressure reached the desired steady-state value, a permissive switch on the main-stage valves was actuated. The main-stage valves did not open, however, until a preset time interval had elapsed. Prior to the run this delay time or heating period could be set for 0 to 6 seconds, and this interval was one of the experimental variables in the study. When the main-stage combustion pressure reached a minimum preset value, a pressure switch actuated the closing of the igniter valve. These operations are indicated on figure 5. The engine was allowed to operate at steady state for only 2 or 3 seconds to conserve the spun chambers. This period, however, was sufficient to establish that a start was entirely satisfactory.

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RESULTS AND DISCUSSION

Data for all the runs are shown in table I, and figure 5 shows a typical run record for the 20-pound-thrust igniter. The important traces are labeled.

No significant differences in performance were observed for the three injectors. Even with the shortest heating periods satisfactory starts were obtained with each at -70° to -80° F. The minimum igniter flow required for the satisfactory operation of each injector was not determined because of operational difficulties with the 4-pound-thrust igniter. It is expected, however, that injector A would require the largest igniter flow and injector B the smallest. This is based on the assumption that propellants injected directly into the igniter flame tend to quench it and reduce its effectiveness. If this assumption is correct, an igniter-injector design would be most efficient when only a small fraction of the main charge is ignited directly followed by propagation of the flame through the remaining charge.

Results with the 20-pound-thrust igniter indicate no unavoidable difficulties with this method of ignition even at the lowest temperatures. In every case operation of the igniter was satisfactory. Each of the explosions or nonignitions in the main stage was traced to propellant-valve malfunctions, to blockage of critical orifices due to ice formation, or to blockage of injection orifices due to tar formation in the previous run. The latter two types of malfunction were the result of improper cleaning and drying of the engine and system between runs.

Results with the 10-pound-thrust igniter indicate that it was marginal at the extremely low temperatures, although quite adequate at -50° F and above. The explosions and nonignitions of the main stage at -70° to -80° F could not all be attributed to equipment malfunction. In many

cases, the malfunction seemed to be due to insufficient ignition energy. Of course, it is possible that a different igniter orientation that more effectively used the available igniter energy would not have exhibited such marginal characteristics.

In no case did the hypergolic igniters malfunction; and the results, in general, illustrate the applicability of separate igniters. Undoubtedly, an increase in igniter flame cross section could improve the efficiency of energy transfer to the main-stage propellants.

In agreement with the data of reference 3, it was observed in this study that the combustion was always smooth in the igniter and that the main-stage combustion often was rough or exhibited low-frequency oscillations.

It was also observed in this study that the main-stage instability invariably started shortly after the igniter flow had decreased to very low values as illustrated in figure 6. This behavior suggests that the system was only marginally unstable and that the piloting action of the igniter flame was sufficient to insure stable flame propagation in the main stage. Analogous behavior with homogeneous fuel-air flames is reported in reference 6. Another possibility is that the propellant flow transients at igniter shutdown triggered an oscillation that otherwise would not have occurred.

Two possible courses are suggested for stabilizing jet fuel - nitric acid combustion. Addition of a more reactive fuel to the jet fuel should decrease the combustion time lag and stabilize combustion. Successful application of this technique is reported in reference 7. Usually the change in reactivity is proportional to the amount of additive, so that, except for marginal cases, very substantial additions are required resulting in a new fuel rather than modified jet fuel.

Perhaps a better approach would be to operate the hypergolic igniter as a continuous pilot. This would not increase the complexity of the system and would permit the use in the main stage of unmodified jet fuel. The latter would be most desirable for tactical applications.

SUMMARY OF RESULTS

The following results were obtained from starting experiments with a 200-pound-thrust jet fuel - nitric acid rocket engine using axial-flow hypergolic igniters:

1. With a 20-pound-thrust igniter (thrust ratio, 0.1) satisfactory starts were obtained at temperatures as low as -80° F.

2. With a 10-pound-thrust igniter (thrust ratio, 0.05) starting was marginal at -80° F, but was satisfactory at -50° F.

3. The onset of main-stage combustion instability (observed in many of the runs) appeared to coincide with the shutdown of igniter flow.

CONCLUDING REMARKS

Although the experiments indicated that no major problems are connected with hypergolic ignition of the jet fuel - nitric acid system, the scale of equipment was too small to permit determination of the ratio of minimum igniter to main-stage thrust as a function of temperature; nor was the effect of altitude evaluated. These, undoubtedly, are functions of engine geometry, injector design, and igniter flame area and location. Therefore, it is doubtful that generalized experiments would give data that could be extrapolated to specific engine designs.

The continuous-piloting technique should be studied further. It offers a promise of eliminating the troublesome combustion instabilities of the jet fuel - nitric acid system without compromising tactical advantages.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, July 26, 1957

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TABLE I. - SUMMARY OF EXPERIMENTAL DATA ON ENGINE STARTING

Run	Main stage injector	Igniter thrust rating, lb	Average igniter propellant temperature, °F	Average main-stage propellant temperature, °F	Igniter combustion pressure, lb/sq in. abs	Igniter fuel flow, lb/sec	Igniter oxidant flow, lb/sec	Main-stage combustion pressure, lb/sq in. abs	Main-stage fuel flow, lb/sec	Main-stage oxidant flow, lb/sec	Time to igniter steady-state pressure, sec
1	A	20	-79	-73	280	0.0217	0.0675	356	0.217	0.676	0.6
2	A	20	-77	-73	---	------	------	---	-----	-----	---
3	A	20	-76	-72	262	.0262	.0607	---	----	----	.58
4	A	20	-76	-72	191	.0256	.0892	310	.103	.962	.29
5	A	20	-81	-74	265	.0221	.0780	346	.289	.677	.42
6	A	20	-82	-72	157	.0233	.0823	278	.223	.767	.55
7	B	20	-80	-71	307	.0215	.0702	281	.224	.599	.40
8	B	20	-80	-75	281	.0235	.0705	349	.233	740	.43
9	B	20	-82	-76	286	.0221	.0643	46	----	----	.49
10	A	20	-79	-79	283	.0198	.0892	302	.321	1.120	.80
11	A	20	-82	-76	213	.0279	.109	351	.318	1.123	.40
12	A	20	-83	-77	254	.0236	.0691	---	----	-----	2.3
13	A	20	-80	-75	323	.0231	.0928	313	----	1.233	2.0
14	A	20	-83	-70	270	.0277	.0918	305	.309	1.057	.61
15	A	20	-82	-75	236	.0402	-----	406	.230	.858	2.65
16	A	20	-76	-72	259	.0396	-----	351	.247	.613	2.38
17	B	20	-83	-78	Zero igniter heating period						
18	B	20	-80	-73	275	.0277	.0918	155	.124	.286	.43
19	B	20	-75	-71	53	.0161	-----	---	----	----	.58
20	B	20	-80	-74	No records						
21	B	20	-79	-73	275	.0352	-----	234	----	----	2.75
22	C	20	-78	-72	315	.0224	.0951	51	----	.529	.49
23	C	20	-60	-49	344	.0268	.0928	412	.251	.669	.65
24	C	20	-76	-73	323	.0272	.0845	294	----	----	.92
25	A	20	-81	-76	302	.0266	.0892	346	.131	.906	.76
26	B	20	-79	-74	318	.0285	.0892	331	.256	.569	.52
27	A	20	-80	-75	321	.0275	.0873	145	.217	.147	.40
28	B	20	-78	-70	281	.0314	.0665	361	.156	.874	.56
29	B	20	-81	-68	310	.0288	.0896	240	.112	.951	.51
30	B	20	-55	-41	321	.0292	.0948	361	.183	.777	.53
31	B	20	-73	-33	321	.0289	.0900	361	.227	.826	.63
32	B	20	-78	-76	319	.0281	.0673	354	.205	.848	.56
33	B	20	-80	-75	317	.0274	.0866	325	.206	.733	.70
34	B	20	-81	-77	294	.0282	.0666	---	----	----	.38
35	C	20	-80	-76	336	.0258	-----	150	.125	.201	.75
36	C	20	-78	-74	280	.0308	.0718	369	.144	.964	.47
37	C	10	-83	-79	299	-----	-----	---	----	----	1.51
38	B	10	-78	-72	304	-----	-----	---	----	----	.64
39	B	10	-81	-74	313	.0246	.0686	205	.315	.459	1.38
40	B	10	-47	-44	326	.0281	.0736	214	.295	.597	.85
41	B	10	-45	-44	295	.0223	.0763	281	.241	.698	.76
42	B	10	-37	-32	292	-----	.0813	337	.262	.804	.72
43	B	10	-78	-74	269	.0258	.0790	---	----	----	.90
44	B	10	-86	-78	244	.0188	.0784	---	----	----	.93
45	B	10	-52	-42	259	.0301	.0883	---	----	----	.98
46	C	10	-42	-36	218	.0265	.0673	---	----	----	.52
47	C	10	+53	+56	246	.0295	.0627	240	.314	.863	.98
48	C	10	+66	+78	229	.0295	.0592	236	.266	.833	1.35
49	C	20	-84	-78	88	.0219	.0670	351	----	1.10	.44
50	C	20	-80	-75	98	.0253	.0645	320	.349	.997	.47
51	C	20	-79	-79	92	.0254	.0665	346	.355	1.076	.50
52	C	20	-68	-48	92	.0258	.0675	338	.300	1.309	.48
53	C	20	-65	-50	246	.0245	.0677	290	----	-----	.49
54	C	20	-81	-77	231	.0258	.0680	350	.211	.955	.68
55	C	20	-81	-77	234	.0215	.0655	361	.259	.892	.37
56	C	20	-81	-77	240	.0250	.0650	340	.305	.905	.53
57	C	20	-81	-77	236	.0261	.0662	---	.291	.922	.52
58	B	20	-83	-78	241	.0253	.0587	---	----	----	1.15
59	B	10	-82	-78	276	.0251	.0667	384	.260	.955	1.62
60	B	10	-82	-78	287	.0238	.0673	329	.267	.971	.73
61	B	10	-82	-78	295	.0230	.0604	---	----	----	.69
62	B	20	-80	-79	251	.0281	.0872	---	----	----	2.09
63	B	20	-80	-79	230	.0290	.0837	300	.220	.913	1.68
64	B	20	-80	-79	230	.0244	.0857	322	.345	1.17	1.73
65	B	20	-80	-79	218	.0269	.0805	---	----	-----	.53
66	B	10	+40	+40	266	.0340	.0804	332	.305	.945	1.03
67	B	10	+40	+40	261	.0334	.0818	347	.281	.911	1.13
68	B	10	+40	+40	235	-----	-----	344	.290	.954	2.44
69	B	10	-10	-10	261	.0335	.0840	307	.279	.948	.86
70	B	10	-10	-10	254	.0340	.0820	331	.308	.974	.87
71	B	10	-50	-50	246	.0297	.0837	317	.303	.939	.87
72	B	10	-50	-50	249	.0310	.0755	320	.324	.990	.79

TABLE I. - Concluded. SUMMARY OF EXPERIMENTAL DATA ON ENGINE STARTING

Igniter heating period, sec	Main-stage valve opening time, sec	Time to main-stage steady-state pressure, sec	Oscillation frequency, cps	Oscillation amplitude, $\frac{lb}{sq\ in.\ abs}$	Run	Remarks
3.55	2.87	2.69	Smooth	---	1	
----	----	----	------	---	2	Exploded on start; ignition lag = 0.29 sec
----	----	----	------	---	3	Exploded on start
3.48	3.57	2.48	Smooth	---	4	
1.40	3.52	3.23	75	±10	5	
3.19	2.09	1.23	Smooth	---	6	After 1 sec, main-stage pressure fluctuated
3.35	2.94	2.56	Smooth	---	7	
3.49	3.27	3.03	80	±5	8	Intermittent chugging
3.31	1.71	1.34	------	---	9	No start; ice blockage
2.74	3.11	1.91	75	±10	10	
2.57	2.84	2.09	70	±10/±50	11	Short period of divergent instability
----	----	----	------	-------	12	Main valve did not open; ice blocked igniter acid line
1.28	3.68	3.47	70	±10	13	
1.43	3.08	2.79	75	±10	14	
0	4.59	4.26	80	±10	15	Main valve opened before igniter reached steady state
0	2.39	2.55	Smooth	---	16	Main valve opened before igniter reached steady state
Zero igniter heating period					17	No records; engine burned out in rough run
3.1	.03	1.06	Smooth	---	18	Main valve did not open fully
---	---	----	------	---	19	No start; valves malfunctioned
No records					20	No start; valves malfunctioned
0	1.47	1.92	95	±5	21	Pressure level unsteady
1.28	1.22	2.2	------	---	22	Main valve did not open fully
.44	3.55	2.46	Smooth	---	23	
2.9	1.48	1.8	Rough	±10	24	Smooth start; burnout at end
3.3	3.3	2.0	Smooth	---	25	
3.45	1.15	1.08	Smooth	---	26	
3.64	1.26	1.05	Smooth	---	27	Main oxidant flow restricted
3.38	1.92	1.43	Smooth	---	28	
3.34	.17	.84	Smooth	---	29	
1.87	.56	1.45	Smooth	---	30	Temperature uncertain
1.88	.13	1.05	90	±5	31	
.99	.11	1.20	Smooth	---	32	
.46	.22	.84	Smooth	---	33	Main pressure dropped slightly after steady value
.58	.05	----	------	---	34	Explosion in main stage; no purge after previous run
.23	.18	1.35	Smooth	---	35	Combustion pressure dropped midrun but recovered
.89	.15	.47	Rough	±10	36	
1.21	.12	----	------	---	37	Explosion on start after good ignition
3.3	---	----	------	---	38	Explosion on start; valve malfunction
2.6	2.48	.93	Smooth	---	39	
3.05	3.6	3.88	Smooth	---	40	
2.56	2.87	1.99	Smooth	---	41	
2.45	4.35	2.53	Rough	±5	42	
2.36	6.1	----	------	---	43	No main-stage start after good ignition
2.17	5.73	----	------	---	44	No main-stage start after good ignition
2.2	1.78	----	------	---	45	Main-stage explosion after good ignition
2.54	----	----	------	---	46	Main-stage explosion after good ignition
2.22	3.51	1.48	100	±120	47	
1.76	2.93	2.01	Rough	±10	48	
.64	.17	.49	80	±20	49	
.63	.19	.47	100	±10	50	
.57	.17	.49	90	±10	51	Became very rough midrun
.60	.18	.49	Rough	±5	52	
.33	.23	.35	20	±50	53	
.77	.24	.44	90	±10	54	
.62	.13	.26	90	±20/±100	55	Became very rough midrun
.42	.19	.49	90	±40	56	Became very rough midrun
.31	.41	.42	80	---	57	80 cps based on igniter pressure
1.39	---	---	------	---	58	Main-stage explosion
1.37	.26	.71	90	±5	59	
1.04	.27	.31	90	±5	60	Hard start
.57	---	---	------	---	61	Explosion after good ignition
.51	---	---	------	---	62	Explosion after good ignition
.94	.59	.66	Smooth	---	63	
.99	.53	.88	80	±10	64	
---	---	---	------	---	65	Main valve did not open
1.97	.05	.65	65	±5	66	
.65	.10	.34	Rough	±5	67	
.44	.10	.55	Rough	±5	68	
.95	.10	.60	Rough	±5	69	
.42	.10	.80	Rough	±5	70	
.95	.25	.66	Rough	±5	71	
.56	.25	.66	Rough	±5	72	

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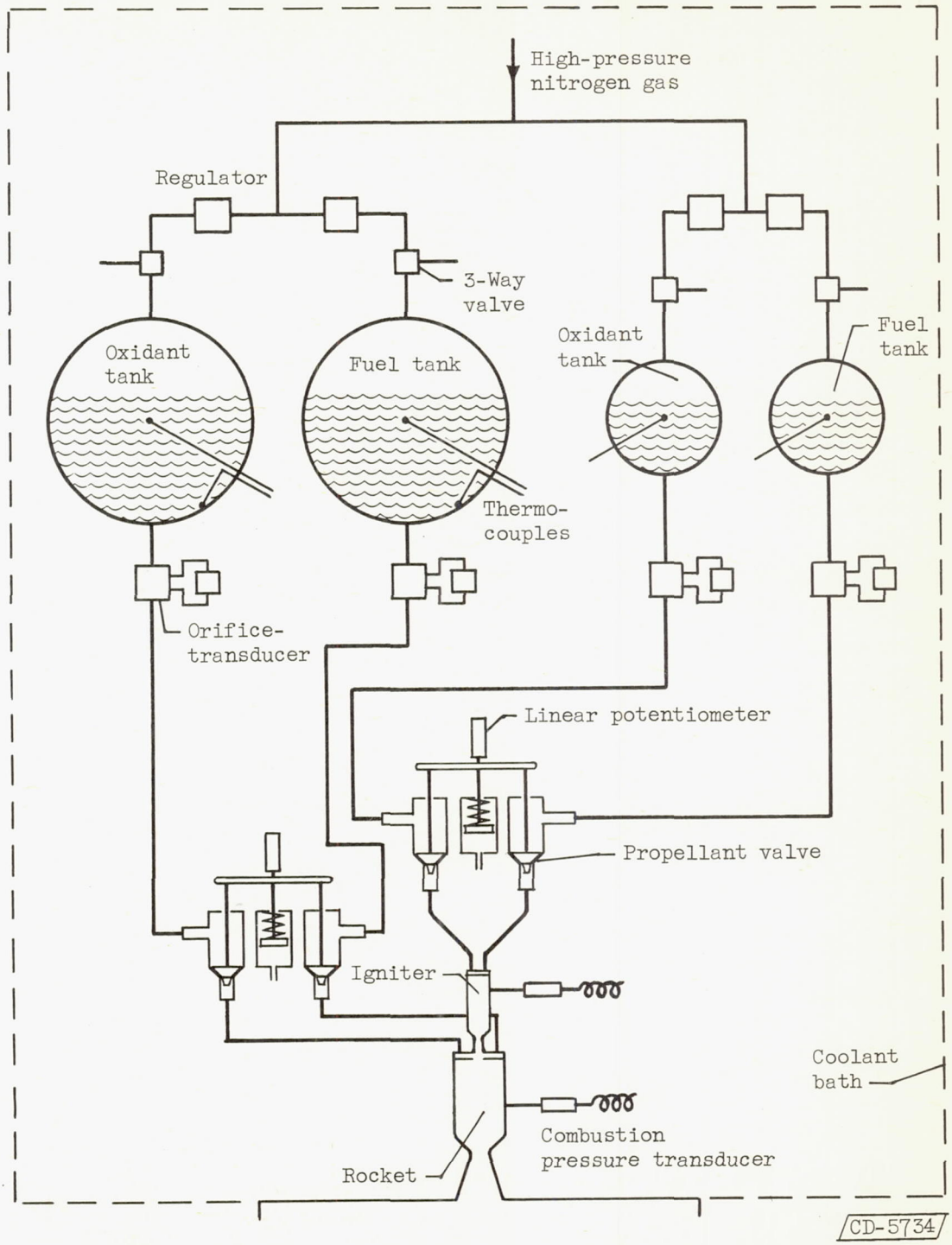


Figure 1. - Schematic diagram of propellant supply system.

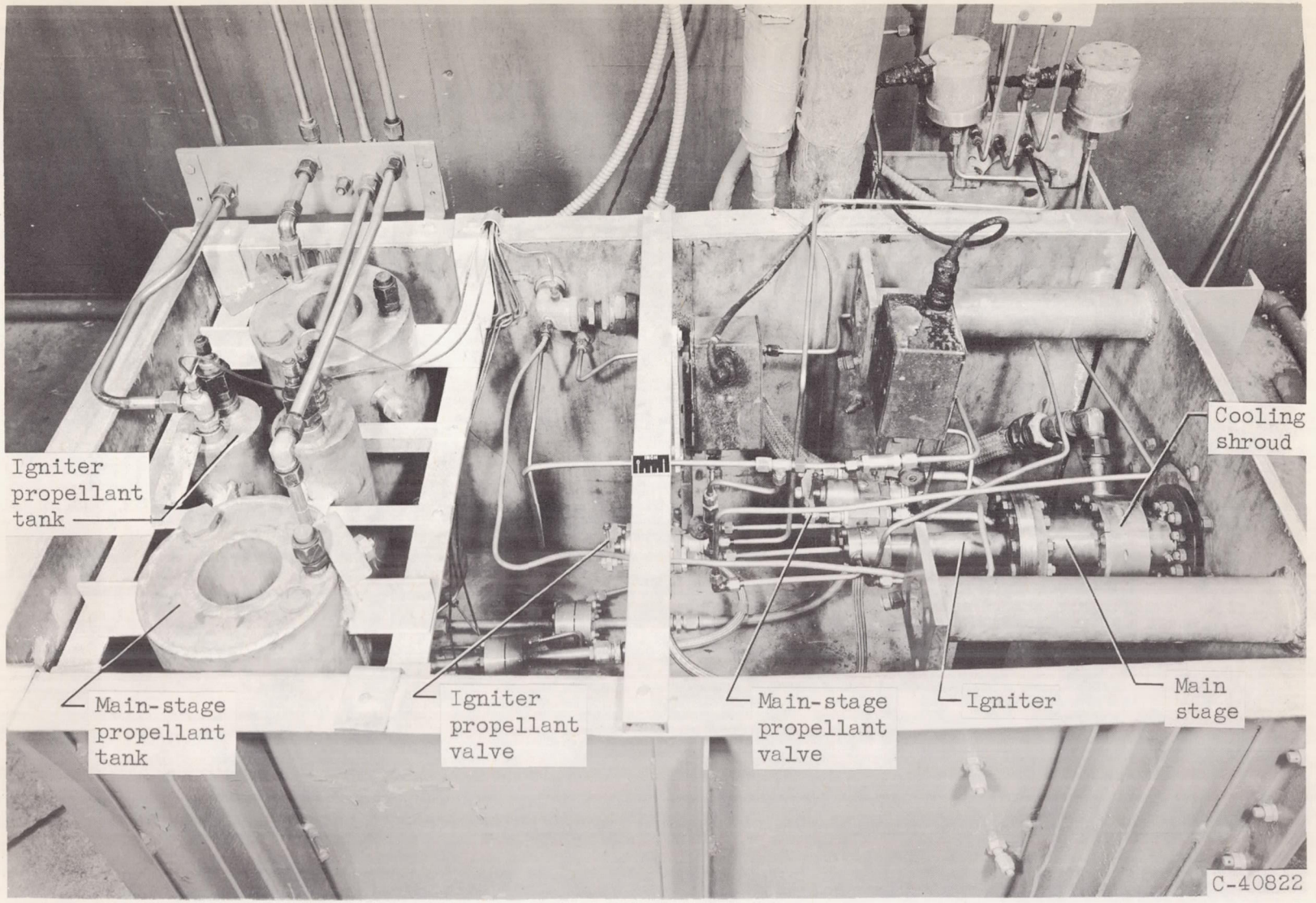


Figure 2. - Photograph of rocket engine and propellant system installed in coolant bath.

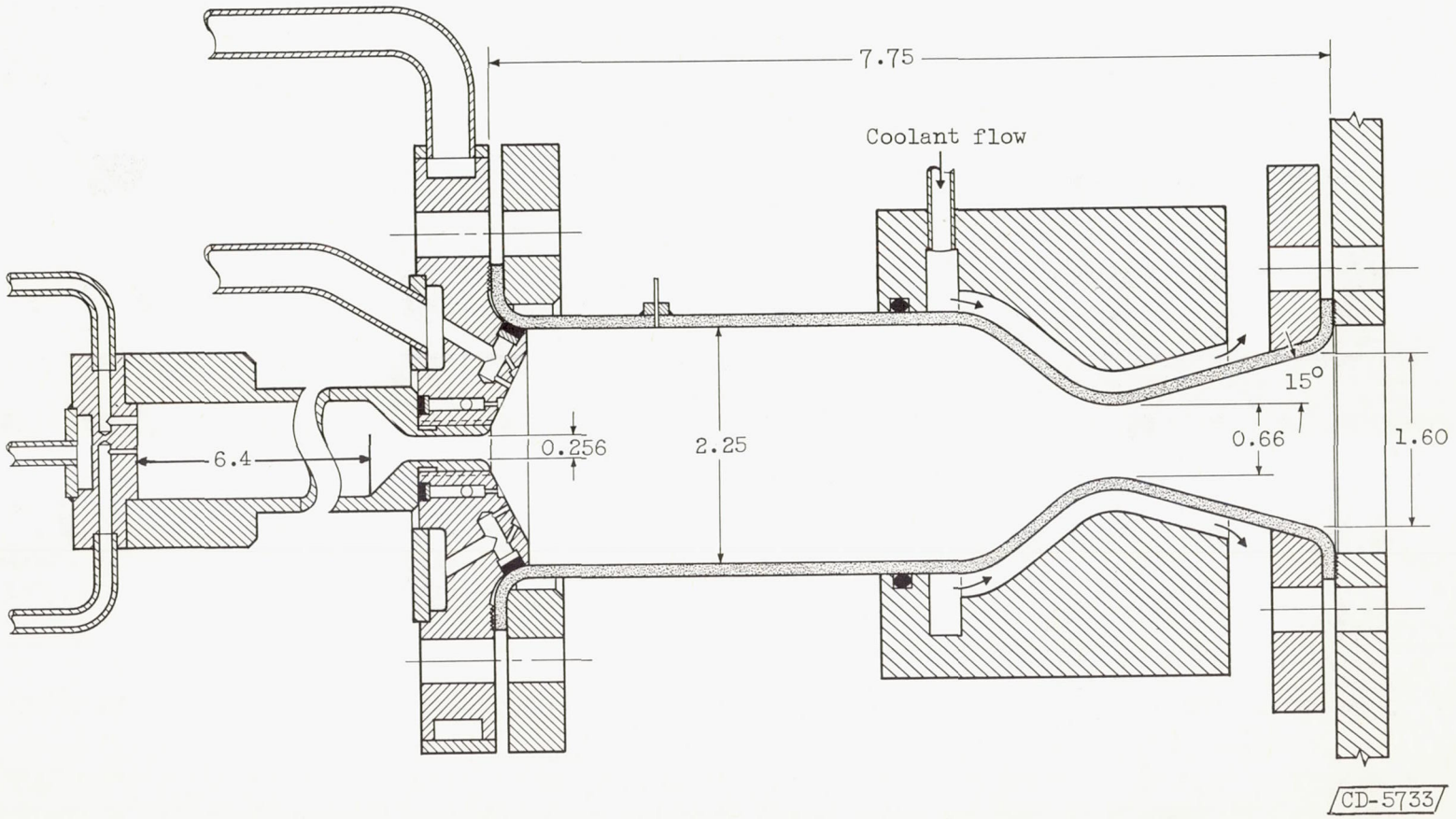
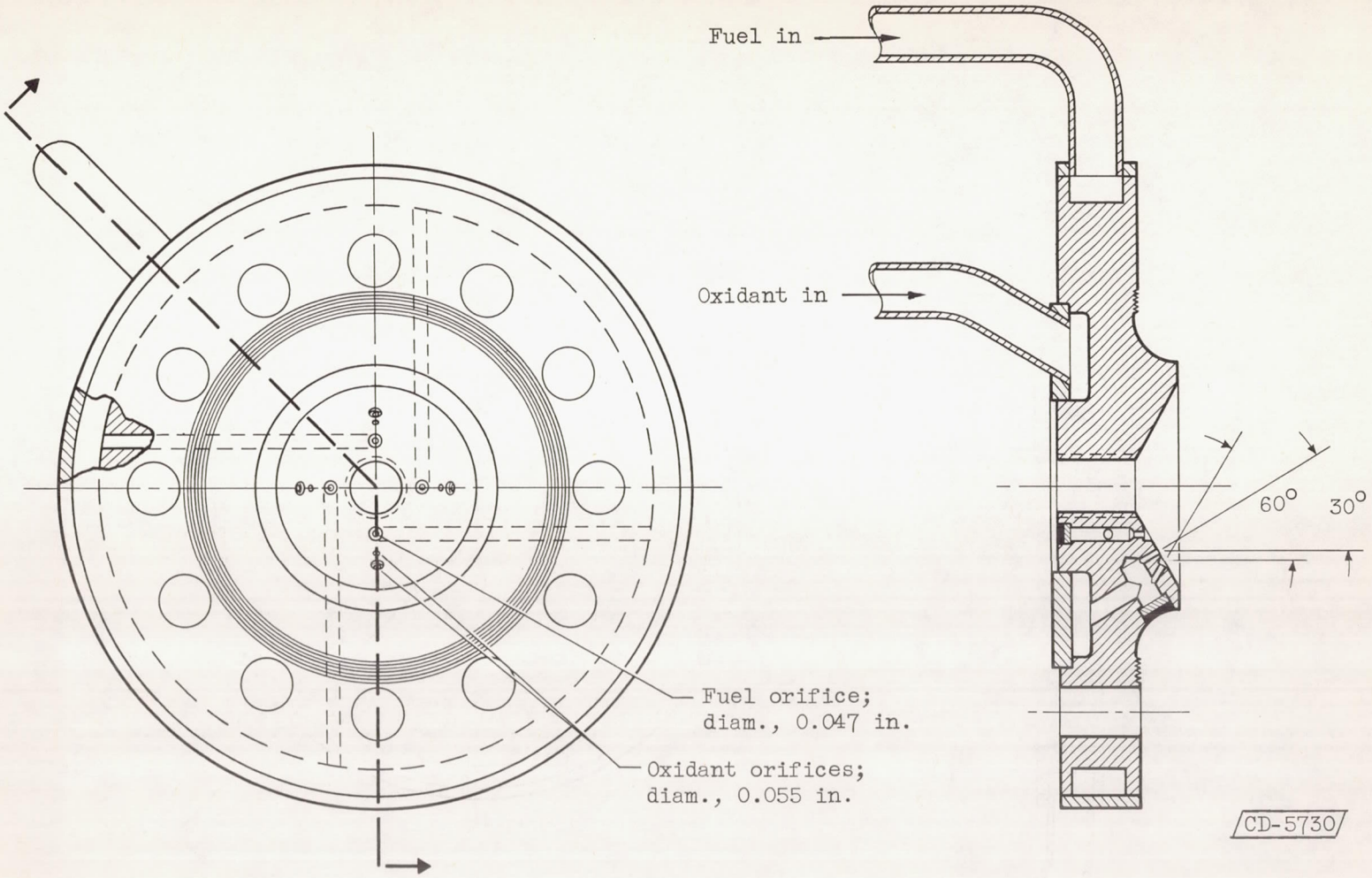
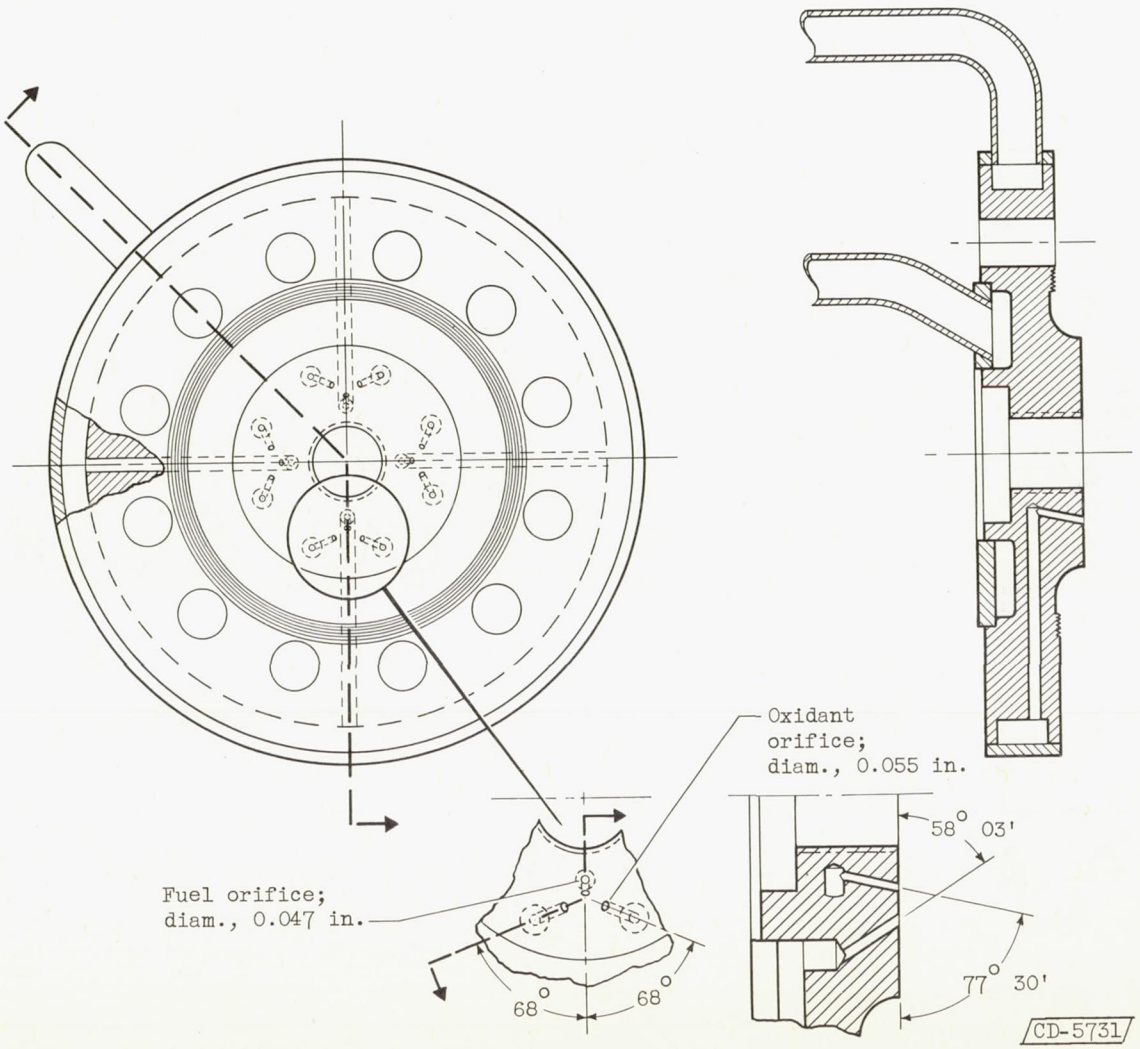


Figure 3. - Cross-sectional view of assembled rocket engine with 20-pound-thrust igniter. Characteristic length, 50 inches. Dimensions in inches.



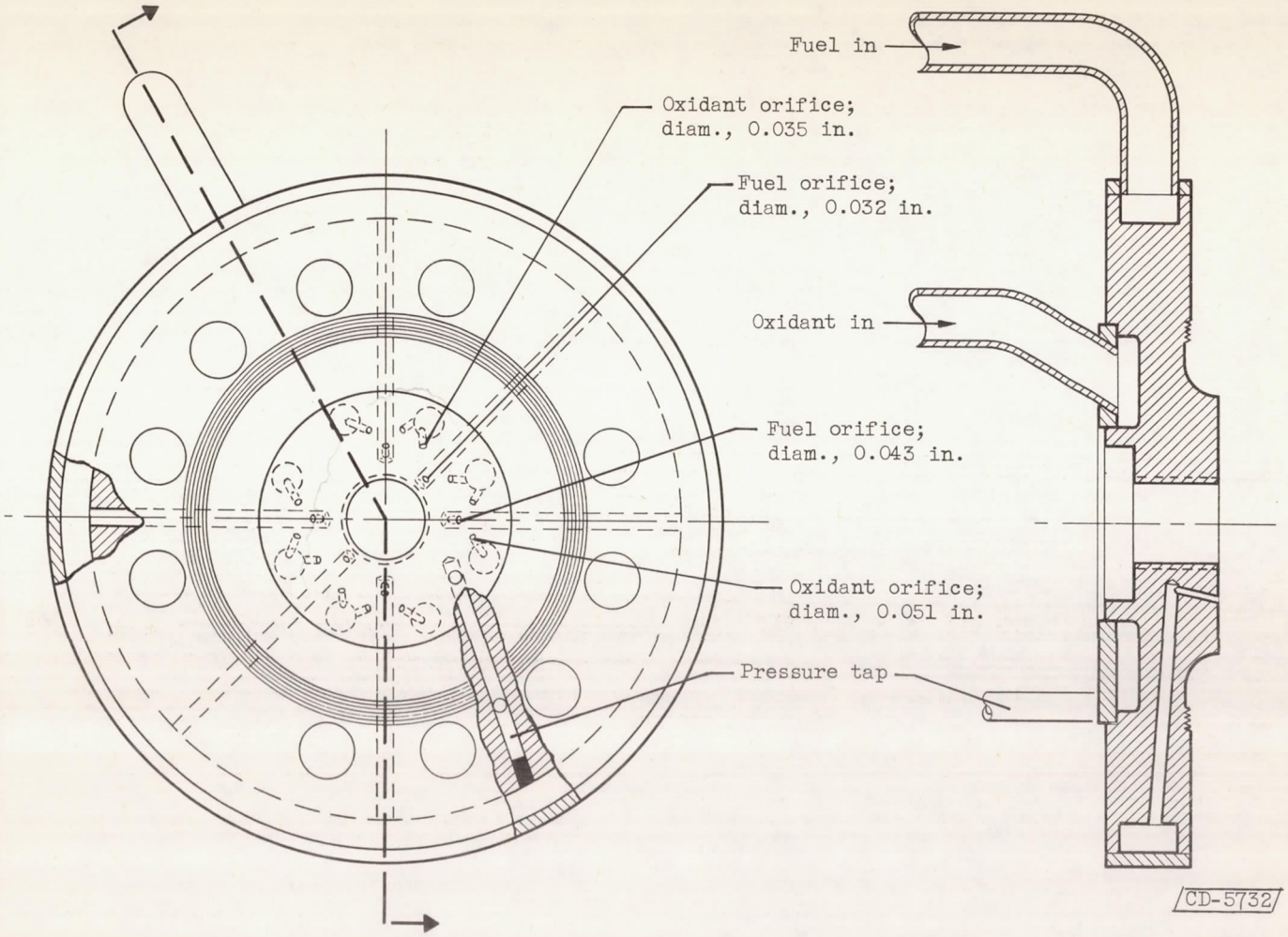
(a) Injector A.

Figure 4. - Details of main-stage injectors.



(b) Injector B.

Figure 4. - Continued. Details of main-stage injectors.



(c) Injector C.

Figure 4. Concluded. Details of main-stage injectors.

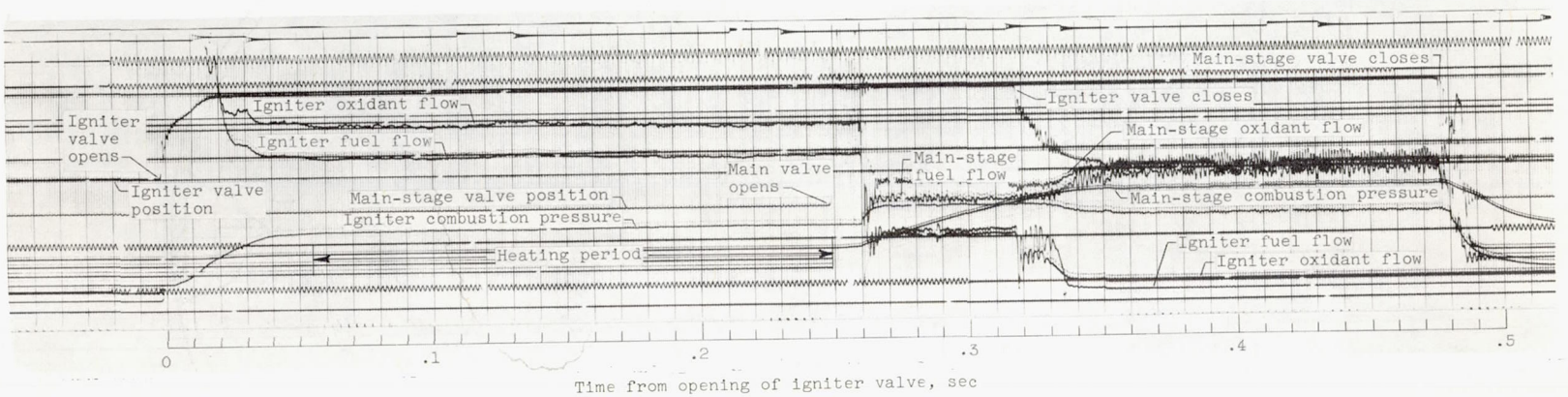
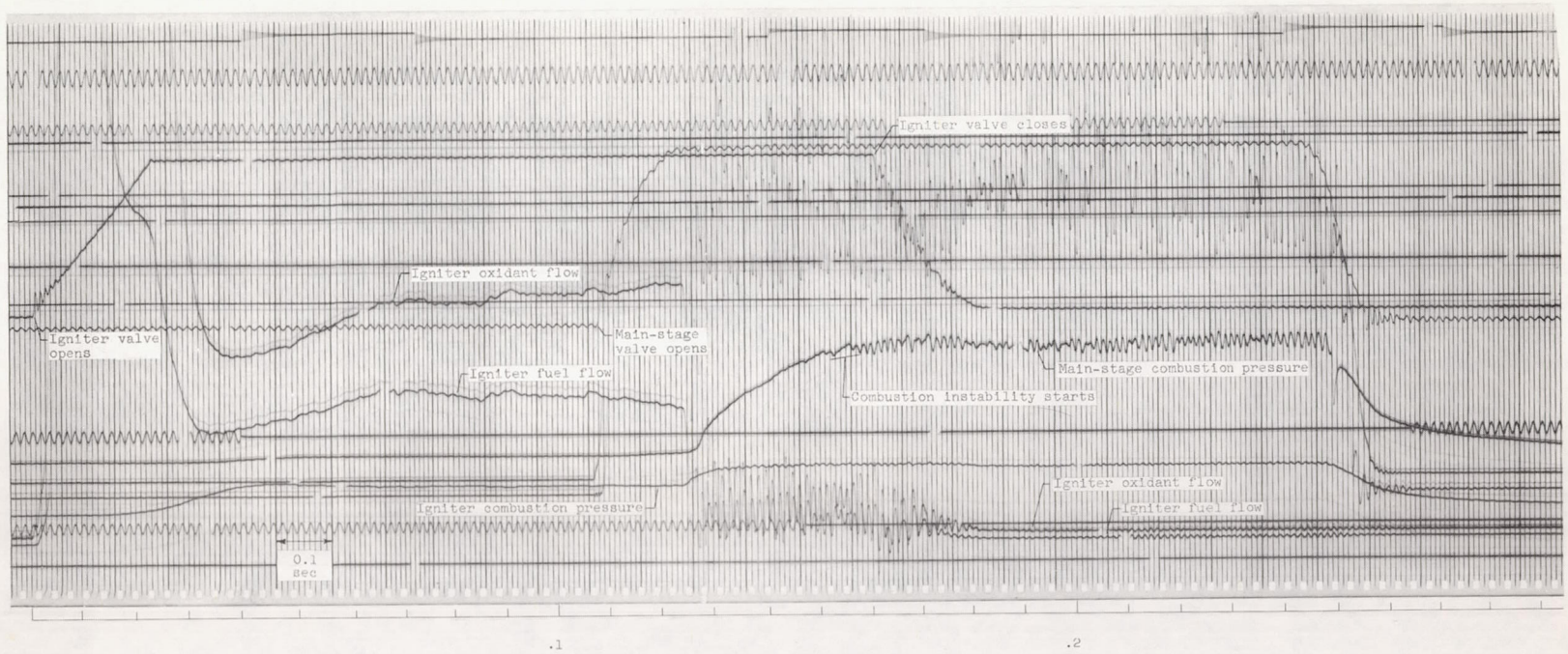


Figure 5. - Typical run data record for smooth combustion.



Time after opening of igniter valve, sec

Figure 6. - Example of records exhibiting combustion instability.